Experimental Study on the Convective Heat Transfer Coefficient of Concrete Mix of Nuclear Power Plant

Yun Lee [a], Jung-Hwan Hyun [b], Jin-Wook Bang [b], Ji-Seok Seo [b], Yun-Yong Kim [b*]
[a] *Dept. of Civil Engineering, Daejeon University, Daejeon 300-716, Korea*
[b] *Dept. of Civil Engineering, Chungnam National University, Daejeon 305-764, Korea*
[*] *Corresponding author:yunkim@cnu.ac.kr*

1. Introduction

During the process of setting and hardening in concrete, the temperature profile shows a gradual nonlinear distribution due to the development of heat of hydration in cement. At early ages of concrete structures, this nonlinear distribution can have a large influence on crack evolution. It is thus important to obtain an accurate temperature history, and to do this, it is necessary to examine the thermal properties of the concrete. In this study, the convective heat transfer coefficient, which represents the heat transfer between a concrete surface and ambient air, was experimentally investigated with test variables such as the velocity of wind, the curing conditions, and the ambient temperature.

For analyses using the thermal equilibrium boundary condition, it is generally noted that most of the heat release by the evaporation of moisture occurs at an early stage. To consider this phenomenon, the existing thermal equilibrium boundary condition has been modified so as to consider the evaporation quantity due to the evaporation effect. Convective heat transfer coefficients for a specific case were then calculated from the modified thermal equilibrium boundary condition using experimental results.

2. Experimental program

2.1 Mixture proportion

The concrete mixture proportions of Reactor Containment Building (RCB) in nuclear power plant (NPP) are given in Table I.

Table I : Concrete mixture proportion

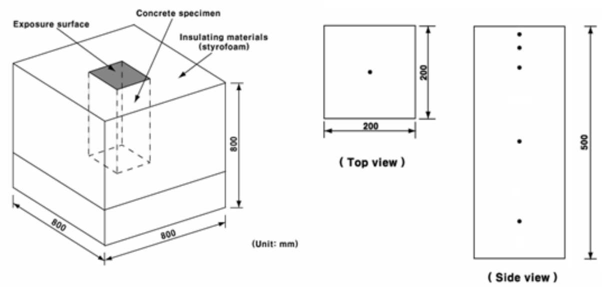
W/B (%)	S/a (%)	Unit weight(kg/m^3)					
		W	C	S	G	Admixture	
						AE	WR
40	44.4	162.7	325.5	748.8	938.7	0.287	2.604

2.2 Test variables

To investigate the effect of the curing conditions and ambient temperature on the convective heat transfer coefficient, the curing conditions, and ambient temperature are selected as the main parameters, as shown in Table II.

2.3 Experimental method

An overview of the test specimen set-up is shown in Fig. 1.



(a) (b)

Fig. 1. (a) Sizes and shape of specimens and insulating materials and (b) locations of thermo-couples.

Rectangular section with 200 mm × 200 mm × 500 mm in Fig. 1(a) was selected. To measure the temperature distribution within the specimen with specimen size, K-type thermo-couples were embedded at the center of the cross-section and five positions along the longitudinal direction of the specimen (Fig. 1(b)). K-type thermo-couples were embedded at distances of 20 mm, 50 mm, 100 mm, 200 mm, and 400 mm from the surface exposed to the air. Fig. 1(b). In order to simulate one-dimensional heat transfer, the specimen was surrounded by insulating materials with a thickness of 300 mm, except at the upper surface of the specimen.

3. Analysis method of experiment results

3.1 Thermal equilibrium condition on the surface

The convective heat transfer coefficient is related to the boundary condition of a concrete surface that is in contact with ambient air. In this boundary condition, the thermal equilibrium condition can be expressed as the following one-dimensional equation (Eq. (1)).

$$h_a(T_s - T_\infty) = \lambda\left(\frac{dT}{dx}\right) \tag{1}$$

where h_a is the convective heat transfer coefficient; T_s is the temperature at the specimen surface; T_∞ is the temperature of ambient air; λ is the thermal conductivity; and dT/dx is the thermal gradient at the surface.

3.2 Convective heat transfer coefficient

Using Eq. (1), experimental results of the convective heat transfer coefficient were analyzed. The given time was determined using the concept of maturity, as shown in Eq. (2), to identify development time of the thermal characteristics of each concrete specimen. The equation is as follows:

$$M = \sum (T_s - T_o)\Delta t \qquad (2)$$

where M is the maturity; T_o is the datum temperature (-10℃); and Δt is the time interval. Saul [1] stated the principle of the maturity concept as, “Concrete of the same mixture at the same maturity has approximately the same strength whatever combination of temperature and age goes to make up that maturity.”

Regression analyses using temperature distributions within the specimen at times having the same maturity were performed. Fig. 3 shows the temperature distribution lines of four specific cases with maturity of test results for a wind velocity of 0.0 m/s and for those without a curing cover. In Eq. (1), thermal gradients dT/dx and temperatures at the specimen surface T_s were obtained using the equations from the regression analyses. In this paper, Eq. (3) is viable, as it is assumed that the convective heat transfer coefficient is constant at the same wind velocity, as previously mentioned. To obtain the heat transfer coefficient using Eq. (4), knowledge of the surface temperature is needed.

$$\lambda_{i+1} = \lambda_i \frac{A_i B_{i+1}}{A_{i+1} B_i} \qquad (3)$$

$$h_a = \lambda_i \frac{A_i}{B_i} \qquad (4)$$

where $A_i = \left(\frac{dT}{dx} \right)_i$ and $B_i = (T_s - T_\infty)_i$

; i refers to each location of temperaure measurement.

4. Experiment and analysis results

4.1 Effect of the curing condition

Table II also shows the difference in convective heat transfer coefficients with curing materials. When curing materials are used, the temperature difference between the center and the surface of the specimen decreases, as the heat release rate into ambient air is reduced. Comparisons of the convective heat transfer coefficients with type of curing materials are shown in Table II. More specifically, without curing materials (i.e., Direct exposure to ambient air), the heat release rate into ambient air increased compared to the use of curing blanket with plastic sheet and Euro-form. Accordingly, when curing blanket with plastic sheet and Euro-form were used, the difference between the center and the surface of the specimen decreases and therefore it is found that the adiabatic effect increases compared to the direct exposure conditions. Additionally, the difference of convective heat transfer coefficients in Euro-form and curing blanket with plastic is small in -10℃ and 20℃. As ambient temperature increases up to 40℃ and 50℃, the differences increases and the convective heat transfer coefficient in Euro-form becomes up to about twice more than that of curing blanket with plastic sheet.

4.2 Effect of the ambient temperature

Under the same curing conditions, the test results (Table II) concerning the ambient temperature (i.e., T= -10, 20, 40, or 50℃) reveal that the convective heat transfer coefficients becomes bigger as the temperature increases. Additionally, the variance of the convective heat transfer coefficients with respect to concrete age also increases within 2 days. Considering the data as a whole, it is concluded that the ambient temperature has considerable effects on the convective heat transfer coefficient, which represents the heat release at the surface.

Table II : Convective heat transfer coefficients

Ambient temperature (℃)	Type of Curing Condition	Convective heat transfer coefficient (W/m^2℃)								
		Age (days)								
		0.5	1	1.5	2	3	4	5	6	Avg.
-10	Curing blanket with plastic sheet	4.0	4.1	3.5	3.8	4.2	4.6	5.0	6.3	4.44
	Euro-form	2.8	2.8	3.7	2.9	2.5	2.9	3.5	4.1	3.15
	Direct exposure	6.1	6.3	7.8	8.8	8.5	10.0	12.1	18.4	9.75
20	Curing blanket with plastic sheet	3.2	2.6	2.7	2.8	2.9	2.6	2.5	1.3	2.58
	Euro-form	2.9	3.6	3.8	3.7	3.2	2.7	2.3	1.0	2.90
	Direct exposure	-	8.2	5.3	5.0	5.9	3.3	3.4	-	3.89
40	Curing blanket with plastic sheet	4.1	3.5	3.8	4.0	5.6	-	-	-	2.63
	Euro-form	6.4	14.4	12.9	10.1	16.5	-	-	-	7.54
	Direct exposure	6.2	-	52.9	78.7	-	1.5	6.1	7.1	19.06
50	Curing blanket with plastic sheet	4.7	4.3	4.1	4.2	5.3	-	-	-	4.52
	Euro-form	5.0	4.2	13.9	12.2	16.0	-	-	-	10.26
	Direct exposure	3.8	76.8	39.2	64.7	15.1	1.4	3.6	4.1	26.09

5. Conclusions

1) In direct exposure to ambient air, the heat release rate into ambient air increased compared to the use of curing blanket with plastic sheet and Euro-form.
2) Ambient temperature has considerable effects on the convective heat transfer coefficient, which represents the heat release at the surface.

Acknowledgements

This work(20101610004J) was supported by the Nuclear Research & Development of the Korea Institute of Energy Technology Evaluation and Planning(KETEP) grant funded by the Korea government Ministry of Knowledge Economy.

REFERENCES

[1] A.Saul, G.A. Principles underlying the steam curing of concrete at atmospheric pressure, Mag. Concr. Res. 2 (6) (1951) 127-140.